Transformer Interaction Caused by Inrush Current

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Abstract - **In power systems with appreciable series resistance, such as those with long transmission lines the voltage drop across the system impedance caused by transformer inrush current may produce an unexpected saturation in transformers already connected to the system. As a consequence, magnetising currents of high magnitudes are produced in those transformers. This establishes a interaction between the incoming and the already connected transformers, which affects significantly the magnitude and duration of the inrush current, which in turn may cause problems on the system such as false operation of transformer differential relays and prolonged temporary harmonic overvoltages. This interaction, which is not normally considered in power system transient studies, is discussed in this paper.**

Keywords: Transient inrush, transformer saturation, sympathetic interaction.

I. INTRODUCTION

The transient phenomenon that occurs when a transformer is energised has been with us since the transformer was invented. Much research has been carried out in order to explain the nature of transformer inrush phenomenon and to derive its mathematical formulation, especially to calculate the first peak of the inrush current under assumed worst conditions [1 - 4]. However, one aspect of this transient which has been largely ignored in the relevant literature is the effect of the inrush current may cause on transformers already in operation, and ***vice versa***.

Transformer inrush current is normally calculated assuming that the transformer is energised onto a system to which there are no other transformers connected. In practice, however, it is almost certain that there will be one or more transformers already in operation when another one is to be energised. On systems with appreciable series resistance, such as those with long transmission lines, this arrangement may develop a transient interaction between the incoming transformer and those that are in operation, which changes dramatically the duration and magnitude of the inrush current. This phenomenon is discussed in this paper.

II. TRANSFORMER INRUSH

It is very well known that the transient magnetising inrush current in a transformer is produced by saturation in the transformer core. This current, which is characterised as being almost entirely unidirectional, rises abruptly to its maximum value in the first half-cycle after the transformer being energised and, thenceforth, decays until the normal steady-state magnetising conditions in the transformer are reached.

As generally accepted, the magnitude and duration of the inrush current depend basically on:

- The point on the voltage wave at which the transformer is energised.
- The residual flux in the transformer core and its sign with respect to the first half-cycle of the steady state alternating flux.
- The saturation or maximum flux density of the ferromagnetic material of the transformer core.
- The total impedance of the circuit through which the inrush current flows.

This is true when only a single transformer is involved in the transient, i.e., when the first transformer is switched onto the system. However, in case of having one or more transformers already connected to the system, the duration and magnitude of the inrush current may change significantly. This happens due to saturation in the transformers in service caused by the transformer inrush itself. Thus, a new item should be included as a factor that also affects the inrush current:

- The saturation level reached by the transformers that are already connected to the system.

This suggests that a transient interaction is established between the energising and the already energised transformers, which may prolong the transformer inrush transient.

III. INTERACTION BETWEEN TRANSFORMERS

As far as the search is concerned, the occurrence of saturation in transformers that are normally in service was first reported by Hayward [5], during field tests made for the purpose of determining the reason for false operation of the transformer differential relays. He found that transient magnetising currents of high magnitude could flow not only in the transformer being switched on but also in other parallel transformers already connected to the system. Also, he found that the transient period of these currents were very long, with the currents decaying at a much slower rate than would be the inrush current of the transformer being switched-on if other transformers were not connected.

This phenomenon was also observed at Fortaleza Substation (CHESF, Brazil). The transformer bank of the Static Var Compensator (SVC) was frequently tripped out when another transformer was energised nearby. The trip out was caused by an offset magnetising current of high level and long duration in the SVC transformer. Similar occurrence was also noticed during energisation of large shunt reactors [6].

The interaction between transformers was extensively investigated in the laboratory using two single-phase transformers of 5kVA [7]. Fig. 1 shows the electrical system used to do this. The parameters of the laboratory supply system were found as being 0.1mH and 0.1Ω for the inductance and resistance, respectively. A resistance R of 0.65Ω in series with the resistance of the system was added for analysing its influence on the phenomenon.

The test consisted of closing the switch S, connecting the transformer T_2 in parallel with the unloaded transformer T_1, which was already connected to the system. Before each switching the residual flux in the transformer T_2 was reduced to zero by using a variable ac source.

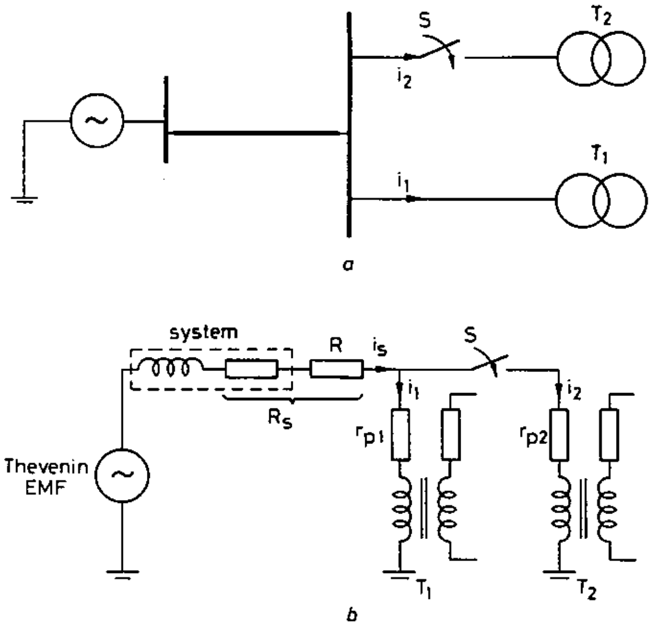

Fig. 1 - Electrical system used to investigate the interaction between transformers. a) System configuration.
b) Schematic diagram of the electric circuit.

Figure 2 shows the currents measured in the transformers during the laboratory tests. As can be seen in this figure, the magnetising current i_1 in the already energised transformer T_1 rises abruptly after the transformer T_2 is switched on, attaining a peak of around 30 times its normal steady-state value

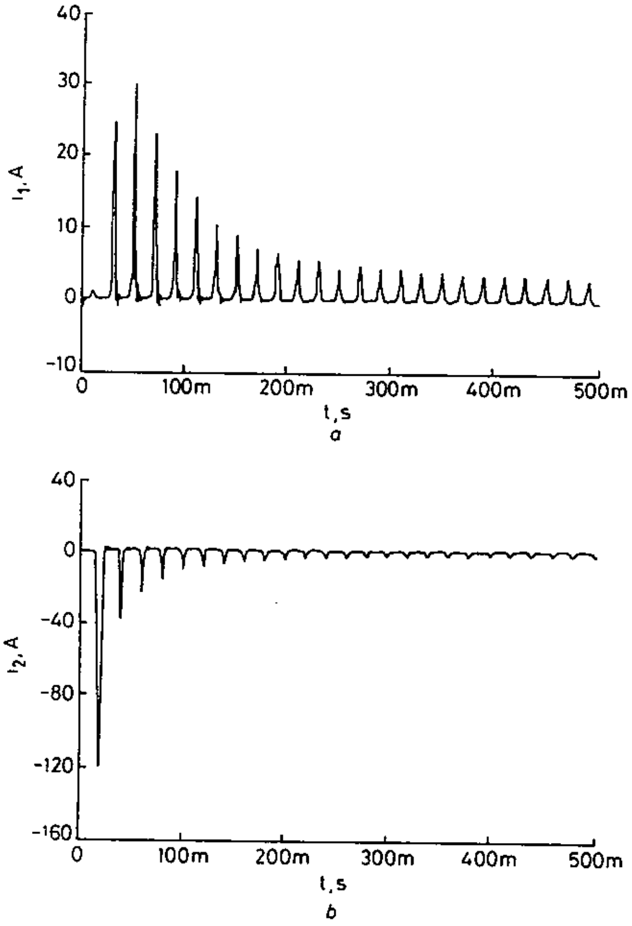

Fig. 2 - Currents measured in the transformers T_1 and T_2.
a) Magnetising current i1 in the transformer T_1.
b) Inrush current i_2 in the transformer T_2.

Computer simulations using SABER simulator was also set up for this system [7]. The calculated magnetising currents in the single-phase transformers are shown in fig. 3. As can be seen, these currents exhibit a reasonable similarity to those measured in the laboratory. This indicates the good accuracy of the transformer model used in predicting the transformer interaction phenomenon observed in the laboratory tests [8, 9].

Simulations with two identical three-phase three-limb core-type transformers of 180MVA, 275/66KV, was also carried out. The winding resistance and leakage inductance of the transformers were assumed to be around 0.1% and 12%, respectively, on the base of 100MVA. Both primary and secondary windings of the transformer were connected in star-earthed. The supply system was assumed to have a reactance of 10%, and a series resistance to be 2% (100MVA base), which are typical values for a system with long transmission lines. Capacitance were not considered.

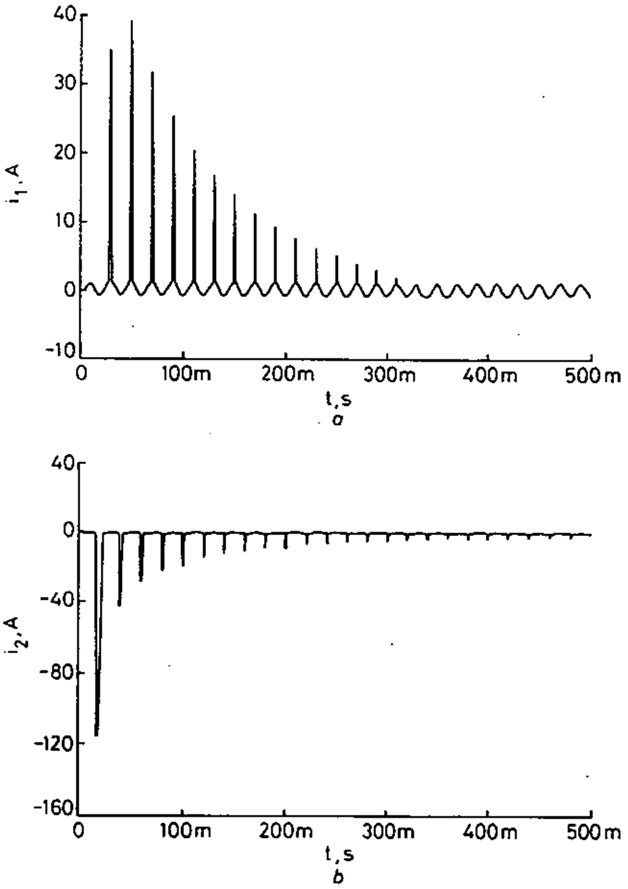

Fig. 3 - Currents calculated in transformers T_1 and T_2.
a) Magnetising current i_1 in the transformer T_1.
b) Inrush current i_2 in the transformer T_2.

The transformer T_2 was energised assuming that all poles of the switch were closed simultaneously, at the instant the voltage of phase b was zero going positive. The "knee" of the B-H characteristic of the transformer core was assumed to be 125% of the nominal peak of the core flux density. The residual flux in the core limbs corresponding to phases a, b and c was set up to be 80%, 0% and -80% of the nominal flux, respectively. Fig. 4 shows the current (phase c) in the transformers T_1 and T_2 during the transient inrush of T_2. Note that the magnetising current i_1 of T_1 reaches values close to the full load current of the transformer, with its peaks of opposite polarity to the peaks of the inrush current i_2, on alternate half-cycles.

For comparison purposes, fig. 5 shows the envelope of the inrush current i_2 of fig. 4b and the inrush current i_0 in the transformer T_2 as it would be if the transformer T_1 was not connected to the system. It can be seen clearly that the interaction between the transformers, a **sympathetic interaction**, modifies considerably the decay of the inrush current, with the current i_2 dying away slower than the current i_0.

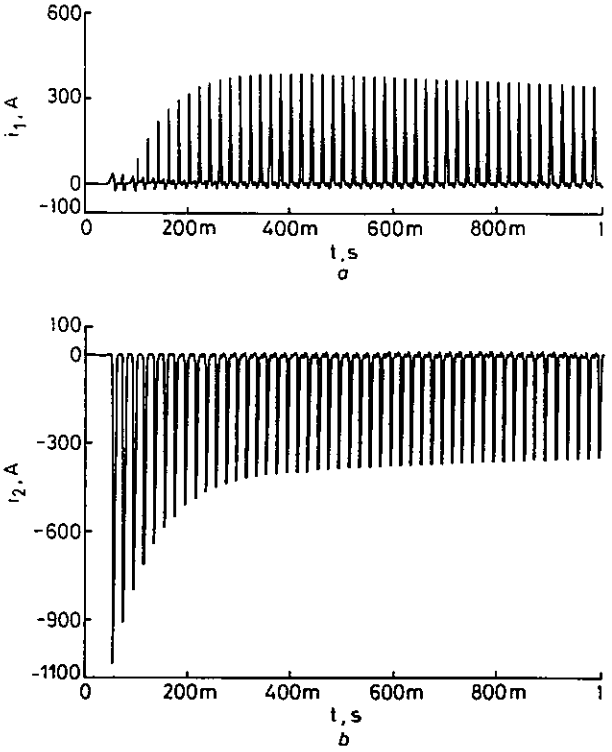

Fig. 4 - Currents calculated in the three-phase transformers of 180MVA. a) Magnetising current i_1 in the transformer T_1. b) Inrush current i_2 in the transformer T_2.

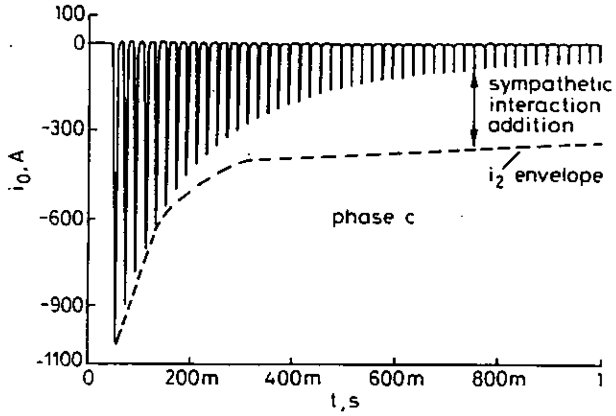

Fig. 5 - Inrush current i_0 calculated in the three-phase transformer of 180MVA being energised without other transformers connected to the supply system.

IV. ANALYSIS OF SYMPATHETIC INTERACTION

The sympathetic interaction may be explained as follows, taking fig. 1 as a reference: Before the switch S is closed only the steady-state magnetising current of the unloaded transformer T_1 flows through the system. When the transformer T_2 is energised a transient magnetising inrush current of high magnitude is drained from the generator (emf), which flows through the system. Due to the almost entirely unidirectional characteristic of this inrush current, the voltage drop across the series resistance *Rs* makes asymmetrical the resultant voltage at the transformer's busbar (point of common coupling). As the flux in a transformer is strictly proportional to the area (integral) of the voltage waveform at its terminals, the flux generated in the transformer T_1 begins to be asymmetrical by an amount which may be given by:

$$\Delta\varphi_1 = \int_t^{t+T} [(R_s + r_1)\cdot i_1 + R_s \cdot i_2]\cdot dt \qquad (2)$$

where $\Delta\varphi_1$ is the flux change per cycle in the transformer T_1 and r_1 is the winding resistance of T_1.

Initially, the flux offset in the transformer T_1 is zero, as it is in service. Thus, the flux change per cycle $\Delta\varphi_1$ produces an increasingly flux offset in the transformer T_1, which drives T_1 into saturation. As a consequence, a sympathetic magnetising current i_1 is generated in the transformer, which increases gradually from the its steady-state value to a considerable magnitude when the transformer saturates fully. It should be noted that the polarity of the transformer saturation is determined by the sign of $\Delta\varphi_1$.

At the same time, a flux change per cycle $\Delta\varphi_2$ is produced in the transformer T_2, which may be given by:

$$\Delta\varphi_2 = \int_t^{t+T} [(R_s + r_2)\cdot i_2 + R_s \cdot i_1]\cdot dt \qquad (3)$$

where r_2 is the winding resistance of the transformer T_2.

Since the polarity of $\Delta\varphi_2$ is opposite in sign to the initial flux offset in the incoming transformer T_2 caused by its energisation, the effect of $\Delta\varphi_2$ is to reduce this initial offset, producing the well known phenomenon of inrush current decay.

From (2) and (3), it can be seen that, at the beginning of the inrush transient, both flux changes per cycle $\Delta\varphi_1$ and $\Delta\varphi_2$ will depend basically on the voltage drop produced by the inrush current i_2. Initially, as the transformer T_1 is not saturated, its magnetising current (steady-state magnetising current) is very small and essentially symmetrical. Therefore, it does not cause any appreciable flux change per cycle.

When the transformer T_1 becomes saturated, as it saturates with opposite polarity to transformer T_2, the peaks of the sympathetic magnetising current i_1 will then occur with opposite polarity to the inrush magnetising current i_2 (on alternate half cycles). As a consequence, the voltage asymmetry on the busbar caused by the inrush current i_2 during one half-cycle is gradually reduced by the voltage drop produced by the sympathetic magnetising current i_1 during the subsequent half-cycle. This will make smaller both the flux change per cycle $\Delta\varphi_1$ and $\Delta\varphi_2$, reducing the rate of change of the magnitude of both the **increasing** current i_1 and the **decaying** current i_2. Thus, some time later the flux change per cycle $\Delta\varphi_1$ will reach zero and hence i_1 stops increasing. Within this cycle:

$$i_1 = -\frac{R_s}{(R_s + r_1)}\cdot i_2 \qquad (4)$$

Thereafter, the polarity of the flux change per cycle $\Delta\varphi_1$ inverts, making smaller the flux offset in the transformer T_1. As a result, the sympathetic current i_1 begins to decay, as does the inrush current i_2. Under this condition, the voltage on the terminals of the transformers presents a waveshape nearly symmetrical, and the flux change per cycle in each transformer will depend basically on the winding resistance of the transformer, i. e.:

$$\Delta\varphi_1 = \int_t^{t+T} (r_1 \cdot i_1)\cdot dt \qquad (5)$$

and

$$\Delta\varphi_2 = \int_t^{t+T} (r_2 \cdot i_2)\cdot dt \qquad (6)$$

It is interesting to note that, in this case, the system resistance *Rs* plays the paradoxical role of keeping both transformers T_1 and T_2 saturated (on alternate half-cycles), with the currents i_1 and i_2 being concomitantly **cause and effect** of saturation in the transformers. That is, the voltage drop across the resistance *Rs* produced by the current i_1 during one half-cycle reduces the flux offset in T_1 and, at the same time, increases the flux offset in the transformer T_2. In the subsequent half-cycle is the current i_2 that produces the voltage drop (with opposite polarity) across *Rs*, increasing the flux offset in the transformer T_1 and, at the same time, reducing the offset flux offset in T_2. This sequence repeats itself, developing a phenomenon called **sympathetic interaction** due to the "sympathy" between the transformers in "sharing" their saturation.

It should be noted that during sympathetic interaction the currents i_1 and i_2 are both decaying, having substantially the same mean value but with opposite sign. In other words, the direct component of the sympathetic magnetising current i_1

will balance the direct component of the inrush magnetising current i_2, making the voltage on the system busbars essentially symmetrical. In this case, the flux change per cycle in the transformers will be very small, depending only on the effective voltage drop across the winding resistance of each transformer itself. This is one of the reason for finding prolonged inrush current in power system supplying large transformers, as these transformers generally present a relatively small value for winding resistance.

Typical envelopes of the sympathetic magnetising current i_1, and the inrush magnetising current i_0 and i_2 are shown in Figure 6. The inrush current i_0 were calculated assuming there were no other transformers connected to the supply system.

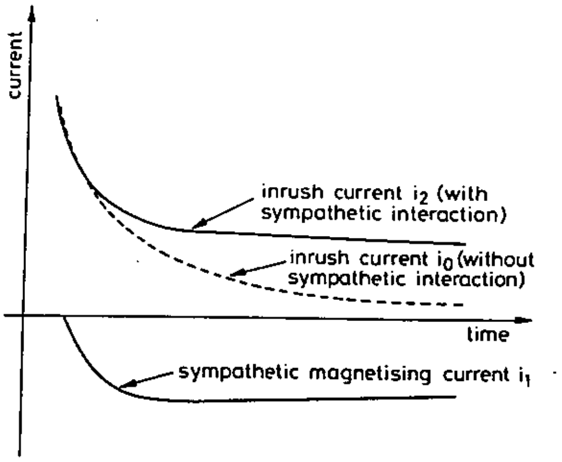

Figure 6 - Typical envelopes of transformer magnetising transient currents.

V. CONCLUSIONS

The interaction occurring in power transformer during inrush transient has been investigated. The results have shown that the inrush current in transformers being connected to system where there are other transformers already in operation decays slower than that generally expected when only one transformer is involved. This phenomenon, which has been called sympathetic interaction, is caused by the asymmetrical voltage drop across the series resistance of the system produced by the inrush current.

The value of the series resistance of the system has been found to be the determining factor in causing this interaction. The impact and duration of sympathetic interaction will depend on the saturation levels reached by the transformers and the energy dissipation pattern in the system. This phenomenon, therefore, should be considered when doing power system transients and insulation co-ordination studies.

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VII. REFERENCES

[1] **BLUME L. F., CAMILLI G., FARNHAM S. B. and PETERSON H. A.**, "Transformer Magnetising Inrush Currents and Its Influence on System Operation", *AIEE Trans.*, **Vol. 63**, pp. 366-375, 1944.

[2] **SONNEMAN W. K., WAGNER C. L. and ROCKFELLER G. D.**, "Magnetising Inrush Phenomena in Transformer Banks", *AIEE Trans.*, **Vol. 77**, pp. 884-892, Oct. 1958.

[3] **NAKRA H. and BARTON T. H.**, "Three-Phase Transformer Transients", *IEEE Trans. on Power Apparatus ad System*, **Vol. PAS-93**, pp. 1810-1819, 1974.

[4] **YACAMINI R. and ABU-NASSER A.**, "Numerical Calculation of Inrush Current in Single-Phase Transformer", *IEE Proc.*, **Vol. 128**, No. 6, pp. 327-334, Nov. 1981.

[5] **HAYWARD C.D.**, "Prolonged Inrush Currents with Parallel Transformers Affect Differential Relaying", *AIEE Trans.*, **Vol. 60**, pp. 1096-1101, Jan. 1941.

[6] **PUENT H.R., BURGESS M.L., LARSEN E.V. and ELAHI H.**, "Energization of Large Shunt Reactors Near Static Var Compensators and HVDC Converters", *IEEE Trans. on Power Delivery*, **Vol. 4**, No. 1, pp. 629-635, Jan. 1989.

[7] **BRONZEADO H. S.**, "Transformer Interaction Caused by Inrush Current", MSc Thesis University of Aberdeen (Scotland), April 1993.

[8] **YACAMINI, R. and BRONZEADO, H. S.**, "Transformer inrush calculations using a coupled electromagnetic model", *IEE Proc. - Science, Measurements and Technologies*, **Vol. 141**, No. 6, pp. 491-498, Nov. 1994.

[9] **BRONZEADO H. S. and YACAMINI R.**, "Phenomenon of Sympathetic Interaction Between Transformers Caused by Inrush Current", *IEE Proc. - Science, Measurements and Technologies*, **Vol. 142**, No. 4, July 1995.